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HYDRODYNAMIC RAM ATTENUATION

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February 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Preliminary experiments have been conducted to evaluate the ability of different inerting agents to attenuate hydrodynamic ram. Standard .50 caliber (12.7 mm) AP bullets and 15/32" (11.9 mm) steel spheres were used to perforate 20 liter metal containers with and without a liquid and Explosafe. Shots were also made with .50 caliber (12.7 mm) AP bullets fired at 220 liter drums with and without a liquid and safety foam. Initial results indicate that the destructive effects of hydrodynamic ram may be enhanced by the addition of Explosafe to

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liquid-containing cells, while the addition of foam may have attenuated the effects of hydrodynamic ram.

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I. INTRODUCTION

For most of the past decade, various groups within the Defense Department have been studying the phenomenon of hydrodynamic ram.[1,2,3] Their efforts have been primarily directed toward attenuating its effects on aircraft fuel cells through improvement of fuel cell design methodology, and by the addition of various energy absorbing materials to the insides of fuel cells.

Briefly, hydrodynamic ram is initiated by the impact of a projectile into a liquid-filled container.[4] Its effects can be divided into three phases: the early shock phase, the later drag phase, and the cavity phase.[5] The shock phase results from the energy transferred to the liquid as the projectile perforates the cell and impacts the fluid, creating a strong hemispherical shock wave centered at the point of impact. This causes an impulsive load on the inside of the entry wall in the vicinity of the entry hole which may force the entry wall to crack and petal In travelling through the liquid, the projectile loses energy to the fluid. This energy is transformed into kinetic energy of fluid motion. The projectile is also slowed by viscous drag. As the fluid is displaced by the moving projectile, a pressure field is generated. This pressure pulse develops gradually as the fluid accelerates, and is of a longer duration, but is less intense than that of the impulsive shock phase. The cavity phase results from the path left by the moving projectile. This cavity is somewhat conically shaped and contains vapor evaporated from the cavity surface, and air which can enter the cavity through the entry hole. Oscillation occurs as the fluid seeks to return to its previously undisturbed state. During this process, additional pressure pulses are generated which aid in the expulsion of fluid from holes in the cell, and contribute to the structural damage of the fuel cell.

One of the major concerns of the users of armored vehicles is the probability of sustained pool-fires resulting from fuel cell destruction and fuel ignition associated with an impacting projectile. Major research efforts have been concentrated on the development of fire-safe fuels.[6] One of the

[1] Thomas Bond, "Response of Fuel Cells of the UH-1D Helicopter to the Hydraulic Ram Forces," BRL Memo. Report No. 2289, April 1973 (AD 910612).

[2] Eric A. Lundstrom, "Fluid Dynamic Analysis of Hydraulic Ram," N.W.C. China Lake, CA July 1971 (AD 889485L).

[3] Thomas W. Lee and Jerome D. Yatteau, "Hydraulic Ram Investigation," University of Denver, Denver Research Institute, Denver, Colorado 80210, March 1978.

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[5] R. E. Ball, "Structural Response of Fluid-Containing Tanks to Penetrating Projectiles," N.P.S. Monterey, CA. Hydrodynamic Ram Seminar, AFFDL-TR-77-32.

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possible ways fuel may become available to sustain a pool-fire would be due to leakage resulting from a cell damaged by the forces of hydrodynamic ram. This memorandum report presents the results of preliminary experiments designed to evaluate the effects of various fuel cell filler materials on hydrodynamic ram. The two materials examined so far are "Explosafe" and the Type IV blue polyether reticulated foam. Explosafe is made of an aluminum alloy foil which is slit and expanded to a hexagonal mesh configuration. Foil mesh batts of this material are then cut and shaped for various applications as a protective mesh in storage containers. Explosafe is manufactured by Vulcan Industrial Packaging, Ltd., Toronto, Canada. Foam is manufactured by the foam division of the Scott Paper Company. This material is currently used as an inerting agent in the fuel cells of some of the combat aircrafts of the U. S. Air Force.

Recent research efforts have demonstrated that Explosafe and foam are effective in attenuating combustion overpressures.[7,8] It is believed that by introducing an energy absorbing medium into fuel cells, that material should provide a shock-absorbing mechanism and act as a retardant for shock wave and pressure pulse generation. Our present objective is to evaluate various inerting systems for military application in attenuating hydrodynamic ram. Additionally, the Target Effects Branch of the Ballistic Research Laboratory has been tasked for FY82 by the Marine Corps Development Center at Quantico, VA, to evaluate the ballistic response of foam and Explosafe when incorporated into liquid-containing fuel cells. As part of a Service Life Extension Program, the Marine Corps is in the process of deciding which inerting system, if any, to install inside the fuel cells of the LVT7A1 amphibious vehicles. Not only should we find out if foam or Explosafe can attenuate hydrodynamic ram, we should also find out if it has any negative effects or no effects at all one way or the other.

Cells damaged by hydrodynamic ram provide a source of fuel for sustained pool-fire burning. By attenuating hydrodynamic ram, we decrease the chances of fuel cell rupture, thus minimizing the availability of fuel for sustained pool-fires. Sustained pool-fires can result in catastrophic kills for armored vehicles. Prior to testing fuel cells from the LVT7A1's with and without inerting materials and a liquid, a series of field tests was conducted using 20 and 220 liter metal containers with and without inerting materials and liquids. This report details the results of our preliminary field tests.

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[7] *A. Szego, K. Premji, R.D. Appleyard, "Evaluation of Explosafe Explosion Suppression System for Aircraft Fuel Tank Protection," Explosafe Division, Vulcan Industrial Packaging Ltd., Rexdale, Ontario, Canada, July 1980 (AD A0 93125).*

[8] *A.J. Holten, "AX Fuel Tank Vulnerability Evaluation Report," Air Force Flight Dynamics Laboratory, AFFDL/PTS Wright-Patterson AFB, OH 45433, July 1974 (AD 922-9166).*

II. EXPERIMENTAL PROCEDURE

A series of 12 shots was fired using .50 caliber (12.7 mm) standard AP projectiles and 15/32" (11.9 mm) steel spheres aimed at 20 liter fuel containers with and without Explosafe, water, and DF 2 diesel fuel. A second series of 9 shots was conducted using .50 cal (12.7 mm) standard AP and 20 mm APIT projectiles aimed at 220 liter drums with and without foam, Explosafe, and water. Two shots were with the 20 mm APIT projectiles, and seven were with the .50 caliber (12.7 mm) projectiles. Shots number 1 through 12 were with the 20 liter containers (Table 1), and shots number 13 through 21 were with the 220 liter containers (Table II). There was only one shot conducted with Explosafe and water in a 220 liter drum. The firings were conducted at the Peep Site Range of the BRL using rifled Mann barrels which are percussion operated and remotely fired. The distance from the muzzle to the target was approximately 12 meters. Two standard electrically conductive velocity screens spaced 60 cm apart were placed 6 meters from the target to make velocity determinations.

The 20 liter containers were purchased from Explosafe of America, Irvine, CA. They were approximately 38 cm high, and had a diameter of approximately 28.5 cm. The tops and bottoms of those cans were used as the entry and exit panels for 11 shots. The projectile travelled 36 cm between entry and exit panels. The sides of a can were used as the entry and exit panels for 1 shot. All the liquid filled containers were filled to the manufacturer's recommended fill-level line, leaving approximately 14% of the volume as ullage space.

The 220 liter drums were standard steel drums with removable tops which were fastened by a retaining metal band. They were approximately 87 cm high and 57 cm in diameter. The foam was provided and installed into those drums by the Scott Paper Co. For the single shot with Explosafe and water, the Explosafe was removed from eleven 20 liter containers and fitted into the 220 liter drum by personnel of the Target Effects Branch. All the liquid-containing targets with inerting materials contained approximately 200 liters of water. The voided volume represented approximately 9% ullage space. The tops and bottoms of those drums were used as the entry and exit panels for all the shots. A 16 mm high speed Milliken camera was used for photographic coverage of the events. Coverage of three shots is unavailable because of camera malfunction. However, still photographs of all the targets are available.

III. TEST FIRINGS

Round #1

A standard .50 caliber AP bullet travelling at approximately 873 m/sec was fired at a container with water but no Explosafe. The top of the can was used as the entry panel. The entry hole was approximately 14 mm in diameter and resembled a typical .50 caliber puncture (12.7 mm in diameter). The exit hole was larger, approximately 23 mm long and 15 mm wide. The effects of hydrodynamic ram were demonstrated by the entry panel being dislodged from 50% of the perimeter of the panel. The left side of the target was squeezed in, and the exit panel was bulged out, but not separated at the perimeter.

Round #2

This target contained Explosafe and water. The projectile was a standard .50 caliber AP bullet travelling at approximately 907 m/sec. The top and bottom of the can were used as the entry and exit panels. The target was destroyed by the bullet. The entry panel was 90% separated from the can with only a 7.6 cm section of the perimeter remaining attached to the top of the can. The exit panel was completely removed and torn by the exiting projectile. The side of the can was split open from the top to the bottom. The split did not occur at the seam.

Round #3

This shot was a repeat of shot #2 with the projectile travelling at 856 m/sec. The entry panel separated from the can over approximately 75% of the perimeter. The entry hole exhibited an outward petaling of the surrounding metal, with a small amount of Explosafe coming through the hole. The sides bulged out in one section, and appeared to be squeezed in in two sections. The exit panel was completely removed and torn by the exiting bullet.

Round #4

For this shot, the bottom of the can was used as the entry panel. This target also contained water and Explosafe, and was struck by a standard .50 caliber AP round travelling at 864 m/sec. The entry panel bulged around the perimeter, but was not separated from the can. The sides were also squeezed in. The exit panel was removed and badly damaged by the exiting projectile.

Round #5

This target contained only Explosafe and air, no liquid. The impacting .50 caliber bullet was travelling at 890 m/sec. The only damage to the panels was entry and exit holes approximately 2 cm in diameter. There was no other damage to the target.

Round #6

This target had air only and was without Explosafe or any liquid. The .50 caliber projectile was travelling at 886 m/sec. Again, the only damage was entry and exit holes approximately 1.5 cm in diameter. There was no other damage to the target.

Round #7

This target had Explosafe, but was without any liquid. The .50 caliber bullet was travelling at 866 m/sec. For this shot, the entry panel impact point was in an area where the handle of the can was spot welded to the top of the can in order to induce tumbling of the round. As a result, the entry and exit panels had larger holes than those of shots #5 and #6. They measured approximately 5 cm in diameter. There was no other damage to the target.

Round #8

This shot was made with the sides of the can being used as the entry and exit panels. The can contained water and Explosafe. The impacting .50 caliber projectile was travelling at 890 m/sec. The entry side exhibited a neat perforation (about 1.5 cm in diameter). There was a large exit hole with tremendous petaling and splitting of the can along the seam. There was also a large conical cavity made into the Explosafe as a result of the cavitation phase behind the round. The left side of the target (top of can) was about 80% separated from the perimeter, and the right side (bottom of the can) bulged around the perimeter.

Round #9

This was the first of three shots using a 15/32" (11.9 mm) steel sphere as the impacting projectile. For this target, the can contained water but no Explosafe. The impacting projectile was travelling at 1044 m/sec. There was a neat entry panel perforation with the panel bulging around the perimeter. The exit hole was also a neat perforation with that panel bulging and separated from about 10% of the perimeter. Both entry and exit holes were about 1.2 cm in diameter. The sides were also squeezed in.

Rounds #10 and #11

The targets for these tests were Explosafe filled cans with water. The projectiles were 15/32" (11.9 mm) steel spheres travelling at 1022 m/sec and 1045 m/sec, respectively. Both entry panels were neatly perforated by the spheres. The panels also bulged at the perimeters. Both cans were split open along their seams. The exit panels were also bulging around their perimeters, but there were no panel separations. In both cases, the entry and exit holes were approximately 1.2 cm in diameter. There was no other damage to the targets.

Round #12

For this test, DF2 diesel fuel was used as the liquid in an Explosafe filled can. A .50 caliber AP projectile travelling at 904 m/sec was used for this shot. The entry panel was neatly perforated (about 1.5 cm in diameter) and bulging occurred at the perimeter of the can. There were two tears along the sides of the can; one extended from the top to the bottom, while the other was only about 12.7 cm long. The exit panel was completely destroyed and removed. Some of the Explosafe material was also pushed out from the can.

Round #13

This was the first shot using the 220 liter drums. This target contained water only, and was hit with a 20 mm projectile travelling at approximately 1101 m/sec. The entry panel or top of drum was completely removed as a result of the projectile's impact. The exit panel was separated over approximately 98% of the perimeter. The entry hole was about 2 cm in diameter, while the exit hole was a large tear about 14 cm long and 14 cm wide with severe petaling. The sides were badly squeezed in.

Round #14

For this shot, the drum contained foam and water, and was perforated with a 20 mm projectile travelling at 1065 m/sec. The entry hole was a neat puncture with the entry panel completely separated. The exit panel was badly bulged and separated about 7.6 cm from the perimeter. The sides of the target were partly squeezed in.

Round #15

For this shot, the 220 liter drum contained water only, and was perforated by a .50 caliber projectile travelling at 889 m/sec. The entry panel was completely separated, and the sides were badly squeezed. The exit panel bulged around the perimeter, and had an exit hole about 5.3 cm long and 2 cm wide. The size of the exit hole is representative of one created by a side-on impacting projectile.

Round #16

This target contained foam and water. The impacting .50 caliber projectile was travelling approximately 910 m/sec. The entry panel bulged around the perimeter, but was not separated. The sides were slightly squeezed in. The exit panel bulged in the vicinity of the exit hole which was about 4.6 cm long and 1.5 cm wide. This hole was also caused by a side-on impact.

Round #17

This target contained water only, and was impacted with a .50 caliber bullet travelling at 859 m/sec. The entry panel of this target was completely separated while the sides were badly squeezed in. The exit panel bulged around the perimeter. The exit puncture resulting from a side-on impact was approximately 5.5 cm long and 2 cm wide.

Round #18

This target contained water and foam. The impacting .50 caliber bullet travelled at 867 m/sec. The entry panel bulged around the perimeter and the sides were squeezed in. The exit panel also bulged around its perimeter.

Round #19

For this shot, the 220 liter drum contained air only. The entry and exit panels experienced neat entry and exit holes. There was no other damage to this target. The .50 caliber projectile impacted the target at approximately 901 m/sec.

Round #20

This target contained foam and soapy water. It is believed that by using soapy water, we promoted better wetting between the liquid and foam, thus minimizing the amount of air trapped within the cavities of the foam inside the target. Because of the compressibility of the air, it is possible to experience an additional attenuating effect which may increase the action

of the foam. The .50 caliber round travelled at approximately 917 m/sec. The entry panel of this target bulged around the perimeter, while the sides were squeezed in. The exit panel also bulged around the perimeter. The results of this shot were similar to those containing plain water and foam.

Round #21

This was the only shot in which Explosafe was installed inside a 220 liter container. Because this material is normally installed by the manufacturer in 20 liter containers, we removed the Explosafe from eleven cans, and installed it in the 220 liter drum. In addition to the Explosafe, the target contained water. The impacting .50 caliber projectile travelled at approximately 905 m/sec. The entry panel bulged and separated, while the sides were squeezed in. The exit panel bulged around the perimeter.

IV. DISCUSSION

The effects of hydrodynamic ram were very evident after each shot with a liquid containing target. The destructive effects appeared to have been enhanced by the presence of Explosafe in the 20 liter containers, especially in the case of the .50 caliber bullets. The geometric configuration of these projectiles is significant; in travelling through the liquid, they always tumble. Additionally, they appeared to have become entangled with the Explosafe material. As a result, these projectiles carried portions of this material with them to the exit panels. This piston-like action may have created an extra loading on these panels, thereby increasing the destructive effects of hydrodynamic ram.

Lesser damage was caused by the 15/32" (11.9 mm) spheres. In addition to having smaller masses, their shape permitted them to travel to the exit panels, experiencing less interaction with the Explosafe. A significant portion of the kinetic energy appeared to have been expended radially into developing fluid motion. In the tests using spheres against targets with Explosafe and a liquid, more damage was done to the sides of those targets than to either of the panels.

In the series using 220 liter drums, lesser damage occurred when the targets contained foam in comparison to those without foam. The differences in structural damage indicate that the foam acted as an energy absorbing medium.

In all the shots made with foam, water, and .50 caliber projectiles, none of the entry panels separated from the targets. The exit panels experienced less bulging, and the exit holes were smaller when compared to the targets shot with water only. The sides were also less damaged.

There were only two shots made with the 20 mm projectiles. After those shots, we decided that the impacting energy associated with each round was too much of an overmatch for the target for us to discern any significant differences in ballistic response due to target set-up. The entry panels separated from both targets. For the target containing foam and water, the exit panel experienced less separation from its perimeter than the target

with water only.

One shot was made with Explosafe and water in a 220 liter drum. For that shot, there is no physical evidence of any increase or decrease in damage to the target when compared to the targets that contained water only. The entry panel separated. The exit panel bulged, and the sides were badly squeezed in. The batts of Explosafe used in this target had been removed from 20 liter containers. It would have been ideal to have had one large cylindrically shaped batt for this target; however, commercial containers with Explosafe larger than a 20 liter capacity are not easily available.

We are presently involved in testing fuel cells supplied by the manufacturer of the LVT7A1 amphibious landing vehicle. These cells will contain different inerting systems. Upon completion of our testing, a definitive judgment and recommendations will be made after evaluating the attenuating properties, in any, of foam or Explosafe.

V. CONCLUSIONS

Subject to the targets and threats used, our tests indicate the following:

1. The destructive effects of hydrodynamic ram were enhanced by Explosafe in the 20 liter containers.

2. Foam acted as a retardant for pressure pulse generation in the 220 liter containers, thereby reducing the effects of hydrodynamic ram.

3. Explosafe demonstrated no positive or negative effects in the one 220 liter target used.

VI. ACKNOWLEDGMENTS

The author wishes to thank Mr. Bernard Izdebski and Mr. Robert McGill for carrying out the firing program at the Peep Site Range of the BRL.

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	PROJECTILE			WATER		EXPLOSAFE			PANEL SEPARATION		SIDES			
Shot #	.50 cal	15/32" Sphere	Velocity m/sec	Yes	No	Yes	No	With DF2 Fuel	Entry	Exit	Split	Intact	Squeezed in	Damage Assessment
1	X		873	X			X		50%	Bulged			X	Badly Damaged
2	X		907	X		X			90%	100%	X			Completely Destroyed
3	X		856	X		X			75%	100%			X	Completely Destroyed
4	X		864	X		X			Bulged	100%			X	Completely Destroyed
5	X		890		X	X			No	No		X		Only entry & exit holes typically associated with a .50 caliber bullet
6	X		886		X		X		No	No		X		
7	X		866		X	X			No	No		X		Entry & exit holes slightly larger than those of shots #5 and #6
8	X		890	X		X			No	100%	X			Completely Destroyed
9		X	1044	X			X		Bulged	10%			X	Partly Damaged
10		X	1022	X		X			Bulged	Bulged	X			Badly Damaged
11		X	1045	X		X			Bulged	Bulged	X			Badly Damaged
12	X		904		X	X		X	Bulged	100%	X			Completely Destroyed

Table I.   20 Liter Containers

			WATER		FOAM		EXPLOSAFE		PANEL SEPARATION		SIDES	DAMAGE ASSESSMENT
Shot #	Projectile	Velocity m/sec	With	Without	With	Without	With	Without	Entry	Exit	Squeezed in	
13	20 mm	1101	X			X		X	100%	98%	X	Completely Destroyed
14	20 mm	1065	X		X			X	100%	2%	X	Badly Damaged
15	.50 cal	889	X			X		X	100%	Bulged	X	Badly Damaged
16	.50 cal	910	X		X			X	Bulged	Bulged	X	Partly Damaged
17	.50 cal	859	X			X		X	100%	Bulged	X	Badly Damaged
18	.50 cal	867	X		X			X	Bulged	Bulged	X	Partly Damaged
19	.50 cal	901		X		X		X	No	No	No	Only entry and exit holes typically associated with a .50 cal bullet
20	.50 cal	917	X		X			X	Bulged	Bulged	X	Partly Damaged
21	.50 cal	905	X			X	X		100%	Bulged	X	Badly Damaged

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